

Alpha-emitters with short half-life induced by protons on heavy elements

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With 23 figures in the text

ABSTRACT

Alpha-emitters with short lifetimes have been produced by pulsed bombardment in a synchrocyclotron. The energies were measured with the help of the magnetic field of the cyclotron, and the decay times with an electronic time analyser. New data for α -emitters in the region between uranium and bismuth are given.

The results from bombardment of thorium agree with previous information about the Th^{224} and Th^{223} series, and yield half-lives for Th^{224} and Th^{223} of respectively 1.05 ± 0.05 sec. and 0.9 ± 0.1 sec. Information about further α -peaks in the 1 sec. region is obtained and the possibility that these are due to the Pa^{224} and Pa^{225} decay series is discussed. The main result from irradiations of Ra is a check of previous data, yielding nuclei with half-lives in the range 0.5 to 40 sec. No α -emitters with lifetimes in the second region were obtained from uranium, lead, thallium, gold and platinum targets. Bombardments of bismuth yield four new α -emitters which from α -systematics are assigned to Po isotopes $\text{Po}^{195-192}$.

Introduction

This paper describes the application of a pulsed bombardment method for studying short-lived α -activities directly in the internal beam of a synchrocyclotron. The proton beam, of maximum 170 MeV, of the Gustaf Werner synchrocyclotron irradiates a thin target, consisting of aluminium coated with a thin layer of a heavy element. After a short bombardment, the energy of the emitted α -rays is determined by means of the magnetic field of the cyclotron, and the half-life is determined in a 20-channel time analyser [1]. The arrangement is shown schematically in Fig. 1. A fraction of the α -rays emerging from the target hit the detector slit and pass to the detector, a ZnS phosphor mounted at the end of a long light guide leading to a photomultiplier outside the cyclotron. The target, the slit and the detector form the elements of a simple 180° -type magnetic spectrometer.

The time analyser is combined with electronic control equipment for the cyclotron oscillator, permitting automatically repetitive cyclotron bombardments with decay measurements in between. The detector is made insensitive during the bombardment. The timing of the irradiation and the 20 time channels is done by a control pulse

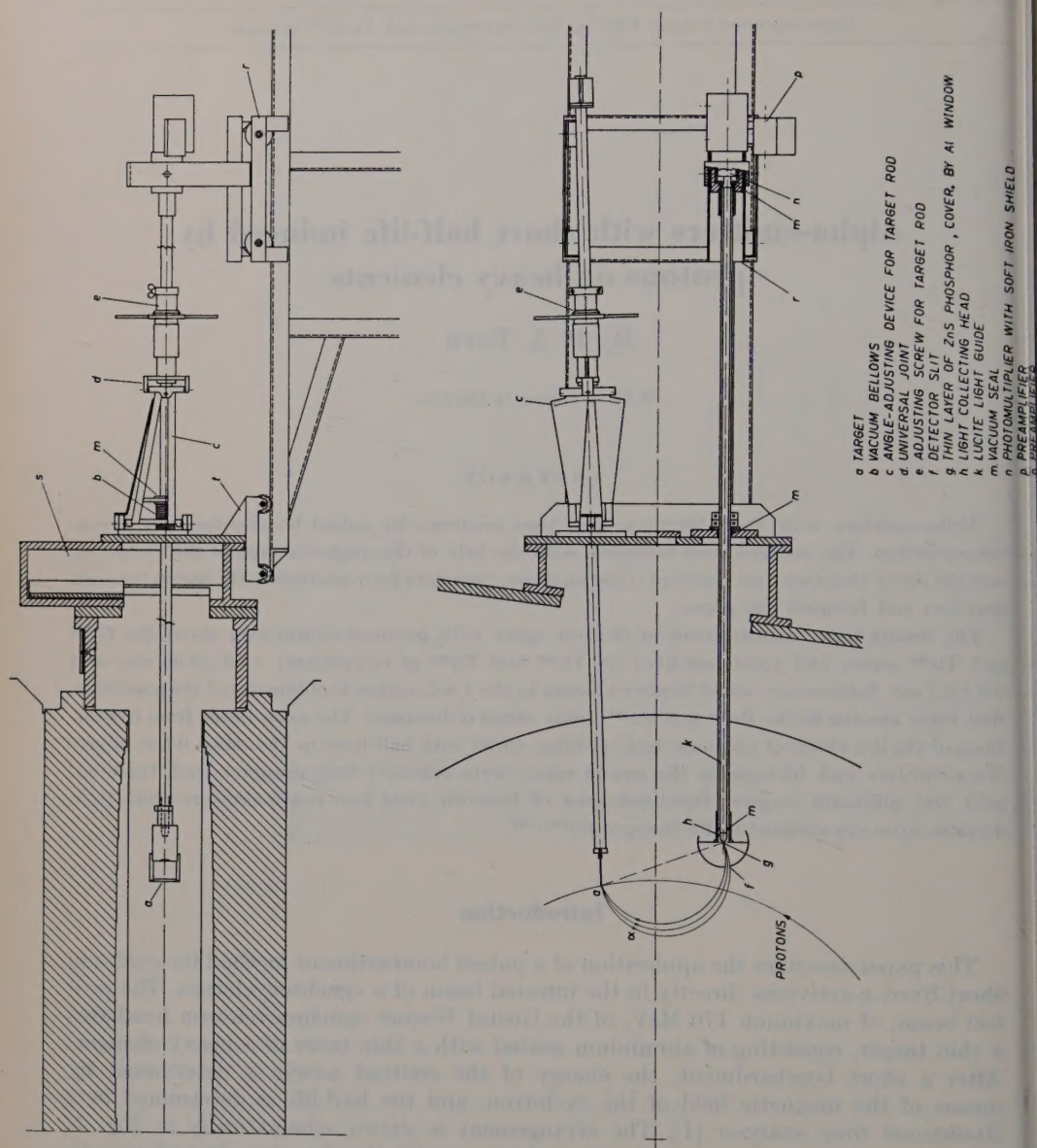


Fig. 1. Spectrometer and detector arrangement in the cyclotron.

generator giving good accuracy and a very flexible range. The count time is successively increased for the later channels to permit better determination of the background. Determination of half-lives can be made with good accuracy.

With the detector fixed, the deviation angle of the target rod is varied in steps and the length position of the rod adjusted to keep a constant target radius in the cyclo-

tron, while the α -energy accepted by the spectrometer is varied. For each setting a series of automatic bombardments and decay measurements is made, giving the half-life for each α -energy. The α -line energy resolution is 1.5–3 % and the transmission approximately 10^{-4} . Multiple proton traversals through the target increase the beam efficiency by an order of magnitude.

The elements investigated are thorium, uranium, radium and bismuth. Lead, thallium, gold and platinum gave no detectable results with this method.

Decay curves were plotted and analysed into components where peaks of different half-lives overlapped. To determine the energy of the α -line the yield for each half-life was plotted as a function of spectrometer setting.

Description of the technique

1. The spectrometer

The principle of the simple 180° -type single-focusing magnetic spectrometer is shown in Figs. 1, 2 and 4. An overall view of the mechanical system is seen in Fig. 3. The α -energy accepted by the spectrometer is determined by the magnetic field and by the distance d_α between target a (Fig. 2) and detector g . The energy is varied by altering d_α .

Two slits, a wider at f and a narrower at g are used to define the α beam. The energy setting of the spectrometer is made from geometrical calculations, while the energy scale is obtained with the help of calibration sources. From Fig. 2 we have for the right-angled triangle having R_t as hypotenuse

$$r_t^2 + (d_\alpha \cos \varphi_\alpha - 180)^2 = R_t^2,$$

$$[R_t + (d_\alpha \cos \varphi_\alpha - 180)] [R_t - (d_\alpha \cos \varphi_\alpha - 180)] = r_t^2.$$

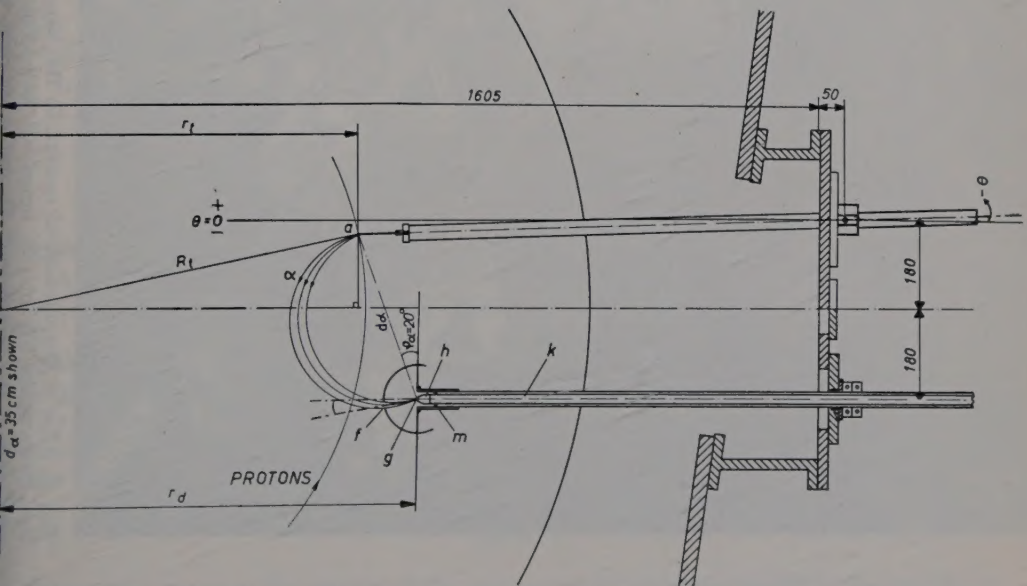


Fig. 2. Details of spectrometer. Distances in millimeters unless otherwise stated.

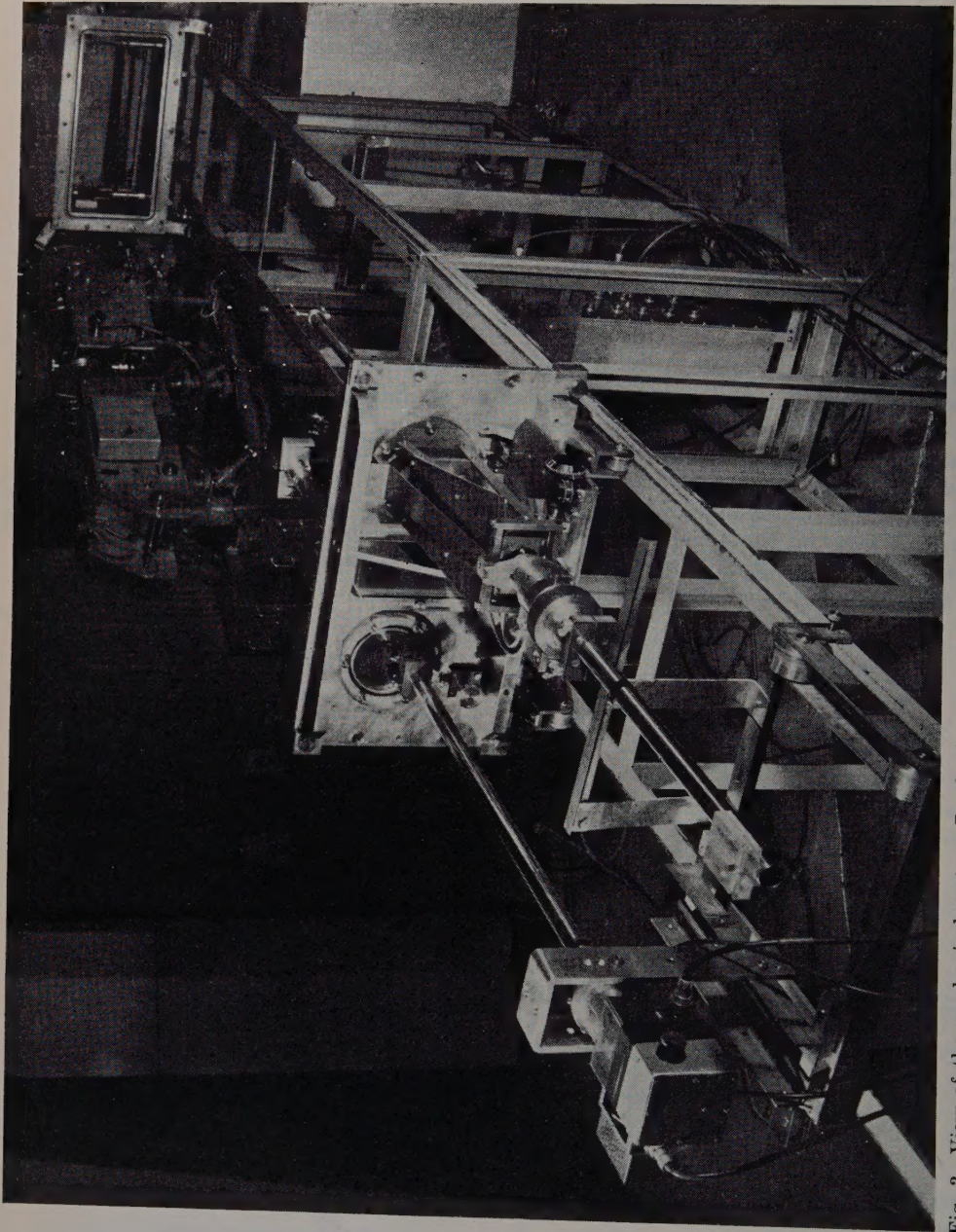


Fig. 3. View of the mechanical system. In the foreground are seen the photomultiplier housing and preamplifier and the light guide to the left and the target rod with adjustment devices to the right. The adjustment motors are seen in the lower

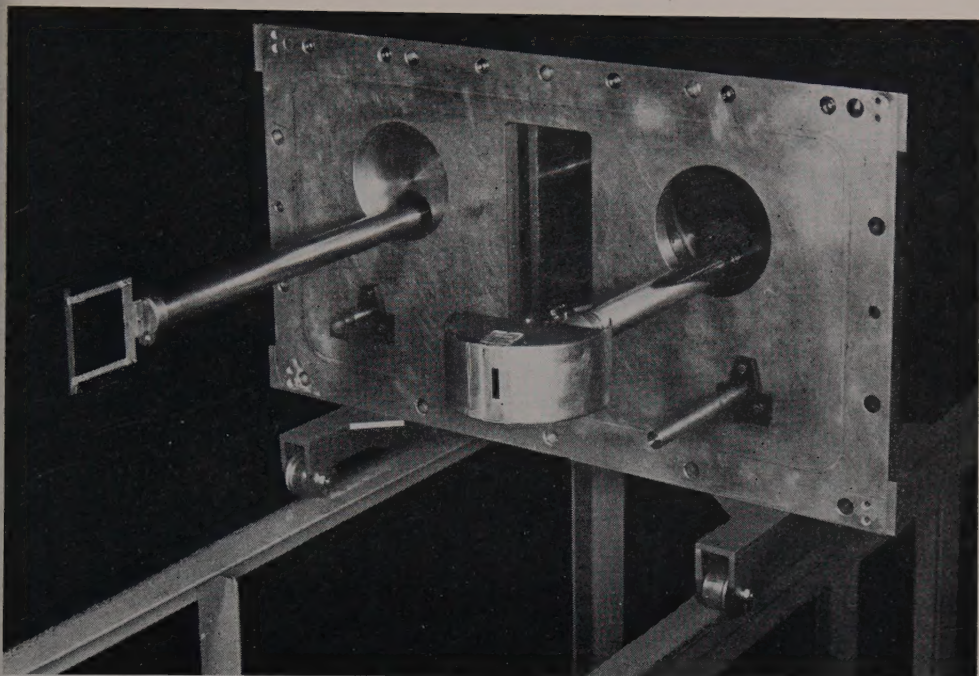


Fig. 4. The rod with target and the light guide with the detector housing pass through vacuum seals in the air-lock flange.

For a given bombardment radius R_t , r_t was calculated for each d_α , taking φ_α constant $= 20^\circ$. The value r_t was set on the adjusting screw of the target rod.

In Fig. 2 we also have

$$\operatorname{tg} \theta = \frac{d_\alpha \cos \varphi_\alpha - 360}{1655 - r_t},$$

$$r_d = r_t + d_\alpha \sin \varphi_\alpha,$$

from which tables of θ and r_d were calculated.

As it is desirable to make adjustments only on the target rod during a series with constant bombardment energy the mean value of r_d in the mostly used range $d_\alpha = 35 - 42$ cm was used. The variation is at most a few millimeters. If the r_d setting chosen is greater than what it should be this causes d_α to be greater and the shift in angle position of the slit also causes somewhat more energetic α 's to be accepted. If r_d is smaller than the calculated value, the effects oppose each other. The errors caused are small, as is that caused by using the value of $1655 - r_t$ for the setting of the target rod, instead of

$$\frac{1655 - r_t}{\cos \theta}.$$

Systematic errors in the setting of the rod as well as inhomogeneities in the magnetic field, of approximate strength 20500 gauss, may cause the α -energy accepted by the

magnetic spectrometer to depart from the calculated value by a larger amount. The spectrometer was calibrated using ThC + C' sources. Calibration curves are shown in Figs. 11-14. The slits used in obtaining Figs. 11-14 were 3.5 mm wide, 14 mm high in the plane of the detecting ZnS surface and 12 mm wide, 25 mm high at a radius of 65 mm from the phosphor. The source width was also approximately 3.5 mm, the height being 15 mm.

From the formula for the resolving power of a semicircular spectrometer of radius ρ we have

$$\frac{\Delta \rho}{\rho} = \frac{1}{2\rho} \{s + w + \rho(\varphi^2 + \psi^2)\},$$

where s and w are source and detector widths, and φ and 2ψ are the angles between the outermost rays and the central ray, in planes perpendicular to the magnetic field and parallel to it, respectively [2]. $\Delta \rho$ is the line width at the base. With the above values this gives

$$\frac{\Delta \rho}{\rho} = 2.4 - 2.1 \% \text{ for } d_\alpha = 35 - 42 \text{ cm}$$

The calculated transmission expressed as the fraction of the total sphere is

$$T = \frac{\varphi \psi}{\pi},$$

which gives

$$T = 3.7 - 3.1 \times 10^{-4}.$$

The measured values for the line half-width in Figs. 11-14 are 1-1.5 %, corresponding to an energy resolution of 2-3 %. The part of the α -particles emitted by a target, that was detected at the top of a line was measured to 2×10^{-4} , mean value for the ThC + C' peaks, using a comparison method with a calibration source and a counter with known efficiency.

From the formula, ψ gives rather small contribution to the half-width. A more optimal ratio of transmission to resolution should be expected at higher ψ values. The ψ value is however limited by the height of the cyclotron beam which is of the order of 15 mm for higher energies.

The expected trend of the calibration curve of E_α versus d_α can be deduced as follows. We have

$$E_\alpha = \frac{Q^2 B^2 \rho^2}{2m} = k d_\alpha^2,$$

where Q and m are the charge resp. mass of the α -particle and B the magnetic field and k is a constant. One can assume that there is a systematic error in d_α , δ , when the spectrometer was set using the calculated values, d_{α_s} , causing

$$d_\alpha = d_{\alpha_s} + \delta.$$

This is because of the difficulty in measuring the actual distance between the target and the detector, as these are inside the cyclotron vacuum tank. The function

$$E_\alpha = k(d_{\alpha_s} + \delta)^2$$

should be adjusted to the calibration points. Normally only the α 's from ThC + C' of 6.05–6.09 and 8.78 MeV were available. For the two alphas we then have

$$E_{\alpha_1} = k ({}_1d_{\alpha_s} + \delta)^2, \quad E_{\alpha_2} = k ({}_2d_{\alpha_s} + \delta)^2,$$

from which

$$\delta \left(\sqrt{\frac{E_{\alpha_1}}{E_{\alpha_2}}} - 1 \right) = {}_1d_{\alpha_s} - {}_2d_{\alpha_s} \sqrt{\frac{E_{\alpha_1}}{E_{\alpha_2}}}$$

and

$$k = \frac{E_{\alpha}}{(d_{\alpha_s} + \delta)^2}.$$

The resulting calibration line is drawn in Fig. 11.

The transmission of the spectrometer varies slightly over the range of d_{α} used, as can be deduced from the calibration peaks of Figs. 11–14. From the known branching ratio of Bi²¹² (ThC) the 8.78 MeV α should follow 66.3 % of the decays while 33.7 % should give α -decay, to 70 % with 6.05 MeV and the rest mainly 6.09 MeV. The transmission is taken to be the ratio of count rate at the peak of a line to the line decay rate of the source. If we use the curves in Figs. 11–14 to get approximate linear correction factors for the transmission in the range 6 to 9 MeV taking the 6.05 peak as a norm we have for the ratio of corrected to uncorrected intensity

$$h/h' = k(E_{\alpha} - 6.05) + 1,$$

where k can be determined from the known value of h/h' at 8.8 MeV.

The ThC + C' source can be considered as weightless. The targets actually used in the bombardments were approximately 0.5 mg/cm² thick. From the approximate formula [3] for the range of heavy particles with charge z

$$\frac{R_z + 0.01 (Z/z)}{R_a} = \left[0.90 + 0.0275 Z + (0.06 - 0.0086 Z) \log \frac{E}{M} \right],$$

where R_z is the range in mg/cm² in element with atomic number Z , R_a is the range in mg/cm² in air, M is the mass number of the ionizing particle and E its initial energy in MeV we can solve for

$$\frac{dR_z}{dE} = \left[\frac{dR_a}{dE} + 0.0261 (1 - 0.143 Z) \frac{R_a}{E} \right].$$

For α -particles of energy 8.8 MeV in thorium we obtain a mean energy loss of 50 keV in a 0.5 mg/cm² target, assuming perpendicular exit. This is slightly increased for lower energies, being 56 keV at 6 MeV. The targets were bent in the edge to get the α -particles pass out more perpendicular. The contribution, from target thickness, to the half-width can be estimated to 1–2 % in half-width. For getting the target or calibration source holder in the same position a jig was used. The expected positioning error is less than 0.2 % in energy. The stabilization in the magnetic field is of the order of 10⁻⁴.

The setting of the angle and the radial position of the target rod is done from the electronic control room about 40 meters away from the cyclotron with the help of electric motors. A bowed cog-rack is fastened to the rod and is in contact with a spiral

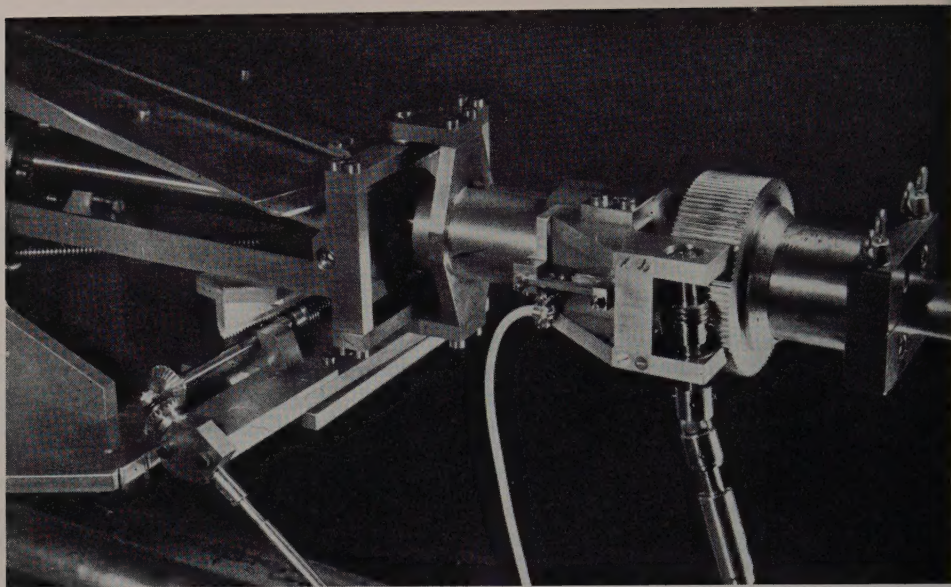


Fig. 5. Cog devices for adjustment of the angle, to the left, and for radial positioning of the target rod, to the right.

cog-wheel mounted on an extension of the flange on an axis driven by the angle motor via a right-angle cog device and a flexible shaft (Fig. 5). The angle motor is placed beneath the rail (Fig. 6). The target rod is spring-loaded to one side in order to avoid play in the setting. The resettability is better than 0.01 degree. The axis for the spiral cog-wheel also turns a fine scale and via a cog device a coarse scale. These can be read in the control room with the help of an RCA industrial television equipment. The television camera is fitted with a long-focus Dallmeyer lens (focal length 17"), to allow placing some 7 meters away from the scale and thus from the cyclotron magnet. In spite of this the camera (Fig. 7) with the sensitive vidicon tube has to be placed in a magnetic shield to avoid distortion of the image (Fig. 8).

The radial position of the rod is varied with a fine adjusting screw driven via a flexible shaft from a motor mounted beneath the rail (Figs. 5 and 6). With a cam device a closing of two contacts is obtained every 0.1 mm in radial position. This lights an indicator lamp. Another lamp lights every mm.

To allow easy set up of the experiment the flange and the photomultiplier are mounted on carts, running on a rail. A large air lock (Fig. 3) admits insertion in the tank without spoiling the main vacuum.

2. The detector

The detector is a thin layer of ZnS-Ag phosphor at the end of a logarithmic-spiral light-collecting head fastened to a 1.8 m long plexiglas light guide [4] with a diameter of 1" (Fig. 1). At the other end is a photomultiplier, EMI 6262, in two concentric

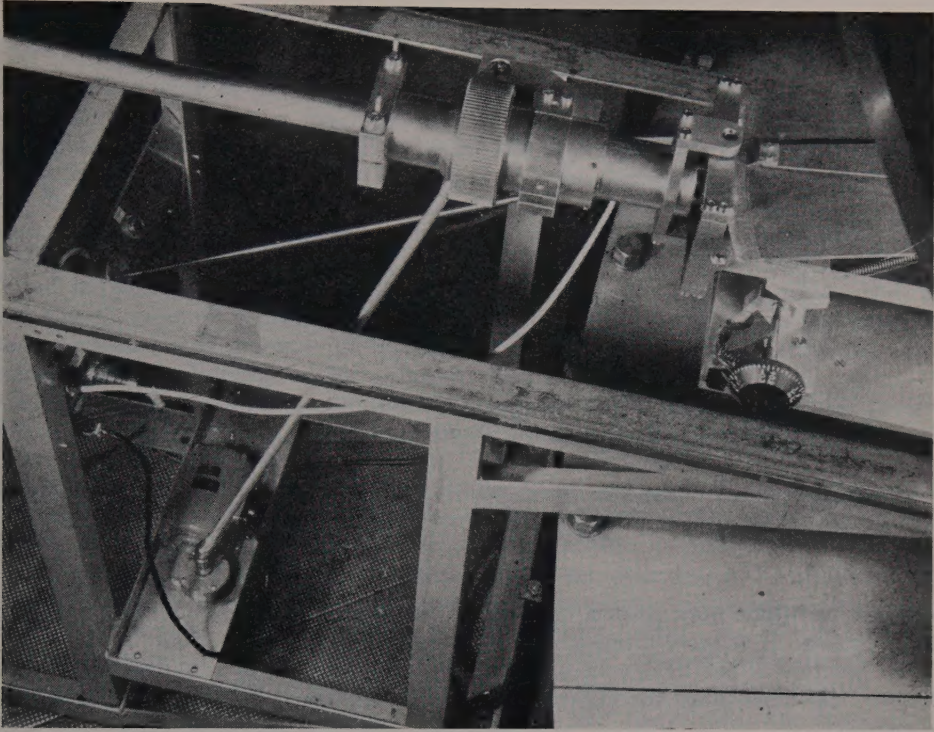


Fig. 6. Adjusting motors with flexible shafts and the angle scale.

soft ion shields, and a preamplifier. The pulses from this are passed to the electronic control room. With this system a satisfactory bias curve is obtained when α -pulses from a $\text{ThC} + \text{C}'$ source are counted (Fig. 9).

The thickness of the ZnS layer should be small, $\approx 10 \text{ mg/cm}^2$ (cf. ref. [5]) in order to have good discrimination against the intense γ -ray background in the cyclotron tank. The powder is dusted onto the plexiglas surface after it has been wetted with silicon oil, and wiped off. Because of the opaque and crystalline appearance of ZnS

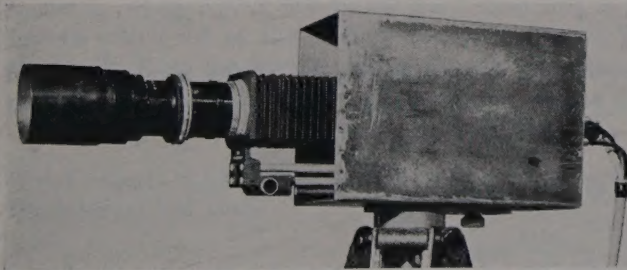


Fig. 7. The television camera.

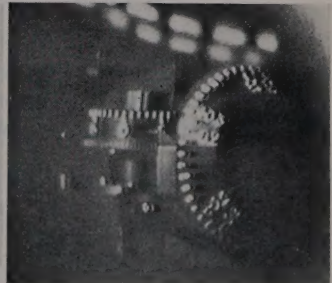


Fig. 8. Television image of the angle scale.

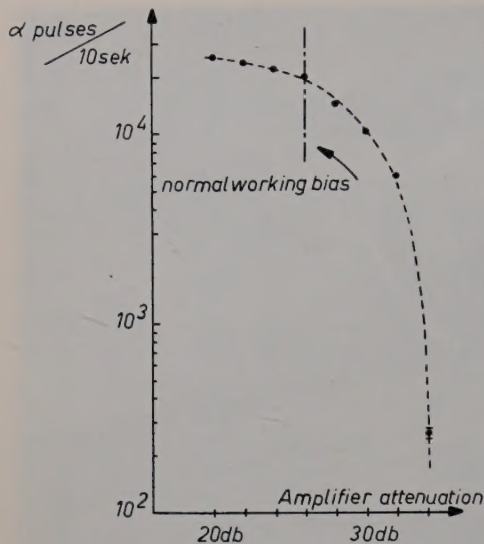


Fig. 9. Integral bias curve for α scintillation detector.

its pulse amplitude only gives a very rough measure of the energy lost (cf. ref. [6]). Its advantage is relative insensitivity to γ -rays and high light yield.

The function of the light collecting head is to avoid light loss, and spread in loss, which would deteriorate the bias curve, meaning decreased stability of the detector sensitivity.

3. The pulsed-bombardment method

Assume that a target, of atomic number A and thickness δ mg/cm² is bombarded in the cyclotron with a mean current i μ A. The formation cross section of the desired nucleus is σ barn. Because of the thin targets the protons make f traversals before they are scattered out of stable orbits because of multiple Coulomb scattering [7].

The number of nuclei produced per second is, using the value for the electron charge, and Avogadro's number

$$\frac{6.24 \times 10^{12} i f \delta \times 10^{-3} \times 6.02 \times 10^{23} \sigma \times 10^{-24}}{A} = 3.76 \times 10^9 \frac{\sigma i f \delta}{A}$$

which is also the number decaying per second at the end of the bombardment if this is sufficiently long to give equilibrium. The total number of nuclei existing at the end of the bombardment and thus decaying after it is then

$$N = 3.76 \times 10^9 \frac{\sigma i f \delta \tau}{A},$$

where τ is the mean life. The statistical information obtained is thus less for shorter half-lives.

If a short bombardment time, of length t_s , is used the yield is decreased to

$$N = 3.76 \times 10^9 \frac{\sigma i f \delta \tau}{A} (1 - e^{-t_s/\tau}). \quad (1)$$

As is well known it is of no use to make t_s longer than a few half-lives. If it is desired to discriminate against a longer-lived activity it may instead be advantageous to use short t_s , for which the yield still increases approximately proportionately to t_s for both desired and background activities. The measurement time is determined by the desire to follow the decay over several half-periods to be sure that no composite decay is present and by the desire for a good value of the background and its decay.

The reactions most favoured in the bombardments are (p, xn) and (p, pxn) . As found experimentally, e.g. for $\text{Bi}(p, xn)\text{Po}$ reactions [8], one can expect that for the heavy elements σ decreases rather slowly with increasing x , the maximum for each x appearing at successively higher energies. This is in agreement with theoretical calculations [9]. Because of the potential barrier the escape of protons during the evaporation process is less plausible, but happens in the initiating cascade process, which only causes the ejection of a small number of particles [10]. For $\text{Bi}(p, xn)$ reactions σ is of the order of 1 barn [8], for moderate x values.

For Th [11] and U [12, 13] we have smaller values especially for large x because of the competition with fission as the fission parameter Z^2/A increases [14]. Experimental values for σ can be used to calculate the fission probability.

In order to determine σ from the experiments one must know the absolute value of the cyclotron current, including f , and the spectrometer transmission for a source of known strength, having the same geometry as the target. The effective current, if , was determined from measurements on 15 hr Na^{24} induced in aluminium target foils by the reaction $\text{Al}^{27}(p, p3n)\text{Na}^{24}$ which has a known cross section [15]. A correction was made for knock-out of a fraction of the Na^{24} nuclei [16]. The transmission was measured with a $\text{ThC} + \text{C}'$ source, the strength of which was also measured with a 4π counter and an α scintillation counter with known geometry.

If the variation of the effective beam and the spectrometer transmission with radius is known, excitation curves can be obtained.

For good measurement of the decay time of an activity it is necessary to know the background, or longer-lived activities present, well. To accomplish this the count time for the later time channels was successively increased, being t_k for the first 5 channels, $2t_k$ for channels 6 to 10, $4t_k$ for channels 11–15 and $8t_k$ for the last channels. The first 5 channels normally covered about one half-life.

After subtraction of the background, the decay curve is constructed by plotting the channel count numbers $n_1 \dots n_i \dots n_{20}$, divided by the appropriate channel time factor k_i (where e.g. $k_i = 8$ for the last 5 channels), at the midpoint of the channel intervals with $t = 0$ at the start of the first channel. When, as here, the intervals are unequally long one has to correct for the fact that

$$\frac{n_i}{k_i t_k}$$

is not exactly equal to the desired instantaneous activity dN/dt at the midpoint of the interval but that

$$\frac{n_i}{k_i t_k} = \frac{\sinh \frac{k_i t_k}{2\tau}}{\frac{k_i t_k}{2\tau}} \frac{dN}{dt},$$

where τ is the mean life. The correction is generally negligible but increases with the ratio of channel time to lifetime, as an example being 5 % for

$$\frac{k_i t_k}{2\tau} = 0.55.$$

For determination of the half-lives, besides the ordinary method of drawing straight decay lines on logarithmic paper, the method of Peierls [17] was used. Peierls also gives the statistical error in the half-life as a function of the ratio of desired activity to background, and also the optimum measurement time for each ratio.

The cross-sections for two nuclides, obtained in bombardments with different t_s and t_k can be compared using the decay curves. The intersection of the uncorrected decay line at $t = 0$, the time of opening the first channel, is called n_0 . This is related to the source decay rate N' at $t = 0$ according to $n_0 = 2\tau\eta N' \sinh(t_k/2\tau)$, where η is the combined geometry and efficiency factor for the detector. Taken together with the previous formula for the yield, Eq. (1), this gives

$$\sigma = \frac{n_0 A}{7.52 \times 10^9 i f \delta \eta \tau (1 - e^{-t_s/\tau}) \sinh \frac{t_k}{2\tau}} \quad (2)$$

$$\left(\text{When } \frac{t_k}{2\tau} \ll 1, \text{ then } \sinh \frac{t_k}{2\tau} \approx \frac{t_k}{2\tau} \right)$$

η is defined as the ratio of count rate to source decay rate when the spectrometer is set at the top of a line. A small error may be introduced by finite target thickness and thus worse resolution if the efficiency, η , is derived from the calibration peaks.

Before the irradiations the cyclotron has to be trimmed to maximum beam intensity. This is done with the help of an ionisation chamber placed near the pole face at small cyclotron radius (20 cm) so that it is hit by scattered protons from a flip target at somewhat greater radius. The flip-target consists of a piece of aluminium sheet fastened to a coil and placed on an axis so that when current is fed through the coil the target raises to the median plane and shuts off the beam. With the flip-target in upright position maximum intensity is trimmed by adjustment of the pulse to the pulsed ion source, filament temperature and high frequency oscillator tensions and inlet of hydrogen. This is all done with the pulsing arrangement of the oscillator switched out. When trimming is ready the pulsing is switched in, and thus the oscillator shut off at a time in the continuously running time analyser cycle several seconds before a pulsed irradiation should happen [1]. During these seconds the flip-target is released and the beam hits the main target. The number of automatic bombardments that could be then obtained was dependent on cyclotron conditions and length of time between bombardments. With 1 second bombardments and 20 seconds between, some 30 irradiations were possible under best cyclotron conditions. With long shut off times the cyclotron had to be trimmed before each irradiation. The reason for this is not quite understood but may be due to adhesion of gases to h.f. electrodes. Therefore "clean up" with the help of heavy r.f. discharges has to take place before a stable beam is obtained.

The deflection of the ionization chamber instrument during the pulsed bombardment is a measure of the beam hitting the target. A comparison of the relative monitor

efficiency for different target radii is obtained by comparing the respective deflections with flip-target up and down. Use of this information in preparing an excitation function requires knowledge of the effective beam at different radii. This effectiveness include factors such as decrease of the circulating beam with increased radius, different multiple traversal factors, and different beam patterns on the target causing different detecting efficiencies. Information about this, excluding the last, can be obtained from the Na^{24} foil measurements.

Besides the ionization chamber monitor, occasionally an integrating monitor was used, consisting of a photomultiplier with a NaI crystal placed at some distance from the cyclotron. The bias of this counter was set to accept only pulses from scattered high energy particles.

Considerations on decay chains

When α -peaks from later members of an α -decay chain whose ancestor is formed in the bombardment are measured, the intensity and half-life observed is not necessarily the same as for the ancestor. The general trend for heavy element α -decay chains outside shell regions is such that for the later members the energy increases while the lifetime decreases, normally giving the result that all peaks decay with the half-life of the parent. A case where the daughter is not sufficiently shorter-lived is drawn in Fig. 10. This is for the case of a constant intensity bombardment of $t_s = 1.2$ sec. length yielding an alpha peak of $T_1 = 1.04$ sec. half-life with a daughter having $T_2 = 0.52$ sec. For the number of the two kind of nuclei N_1 and N_2 we have

$$\frac{dN_2}{dt} = \lambda_1 N_1 - \lambda_2 N_2 \quad \text{and} \quad \frac{dN_1}{dt} = C - \lambda_1 N_1,$$

where C is a constant, during the bombardment, and

$$\frac{dN_1}{dt} = -\lambda_1 N_1$$

afterwards. With $N_1 = N_2 = 0$ at $t = 0$, at the start of the bombardment, we obtain

$$N_1 = \frac{C}{\lambda_1} (1 - e^{-\lambda_1 t}) \quad \text{and} \quad N_2 = \frac{C}{\lambda_2} (1 - e^{-\lambda_2 t}) + \frac{C}{\lambda_1 - \lambda_2} (e^{-\lambda_1 t} - e^{-\lambda_2 t})$$

during the irradiation. For $t = t_s$, $N_1 = N_{10}$ and $N_2 = N_{20}$. Afterwards, for $t > t_s$ we obtain

$$N_2 = N_{20} e^{-\lambda_2(t-t_s)} + \frac{\lambda_1 N_{10}}{\lambda_2 - \lambda_1} \left[e^{-\lambda_1(t-t_s)} - e^{-\lambda_2(t-t_s)} \right].$$

The decay rates $\lambda_1 N_1$ and $\lambda_2 N_2$ are plotted in Fig. 10. It is seen that $\lambda_2 N_2$ reaches its maximum some time after the end of the bombardment.

The intensities of the peaks may also be different if K -capture branching occurs and if recoil separation take place. For neutron-deficient nuclei, such as produced in the thorium bombardments the expected trend is that the ratio of α -decay to K -capture probability increases for decreasing neutron numbers. This is because the energy dependence is still stronger for α -decay than for K -capture [20]. The energy

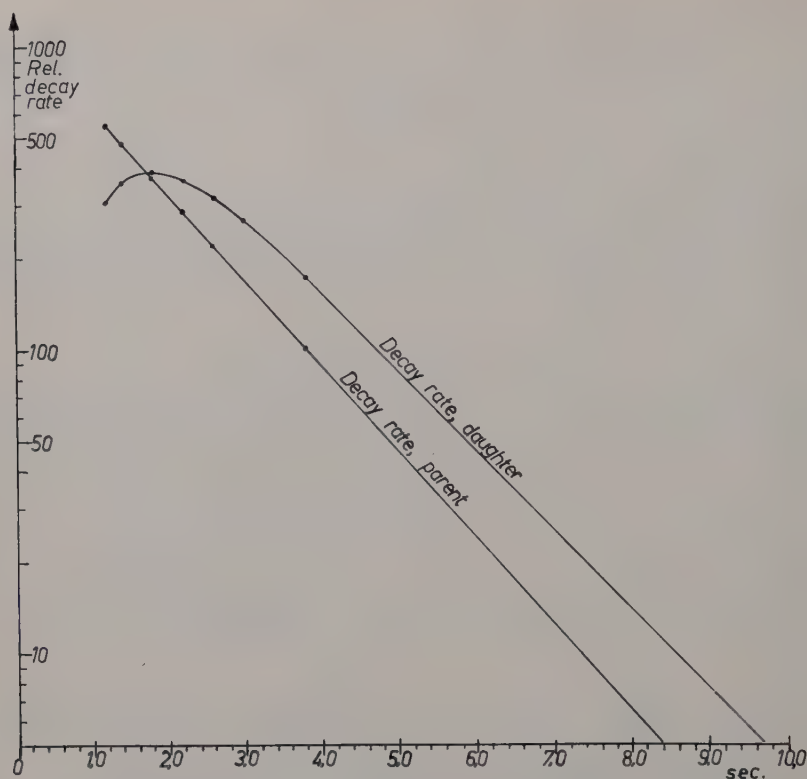


Fig. 10. Theoretical decay rate of parent and daughter activities produced in a short bombardment and having half-lives of 1.04 and 0.52 sec. respectively. The irradiation time is 1.2 sec.

to half-life relation for α -emission can be seen from plots of the type illustrated in Fig. 18, while the trend of K -capture decay probability can be derived from K/β^+ -ratios and ft -values for allowed β^+ -transitions [18]. The possibility of formation, directly or via K -capture, of daughters in a chain together with the parent normally does not affect the peak ratios as it generally yields appreciably shorter-lived nuclei.

Recoil separation is the possibility of escape from the target of decaying nuclei because of the recoil. The alpha peak of the daughter then decreases if the lifetime is long enough (a fraction of a μ sec) to permit the nuclei to move appreciably before decaying. The range of the recoils in air for ThC' is about 0.2 mm [19], indicating that the loss using a target of 0.5 mg/cm² thickness should be small.

Measurements and results

Thorium

The target was a thin layer, 0.5 mg/cm², of ThO_2 on 0.0005" thick aluminium sheet, and was prepared by applying many layers of nitrate, in acetone and collodium, igniting and polishing for every layer, in order to get even thickness.¹

¹ The target was supplied by the Atomic Energy Research Establishment, Harwell, England.

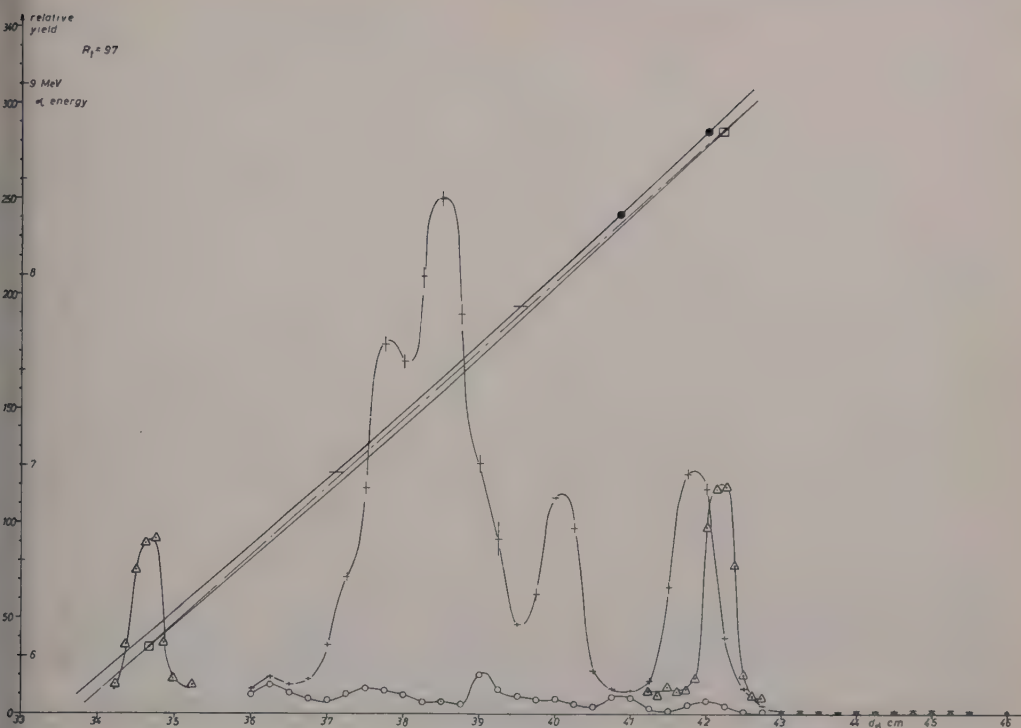


Fig. 11. Th target, relative yield for bombardment radius $R_t = 97$, expressed as pulse number in the first channel divided by the summed monitor value, as a function of spectrometer setting d_α . $t_s = t_k = 1.2$ sec. The background is also plotted as the mean value of the counts in channel 6 to 10 divided by the total monitor value. Calibration lines are also drawn (see text). The statistical errors of the points are shown by the height of the crosses. The statistical errors in the background curve are only a small fraction of the diameters of the circles. Triangle-marked points are from a ThC + C' source.

In a first series of bombardment a bombardment time and channel time of $t_s = t_k = 1.2$ sec. was used. The decay was followed during a time of 10 or 15 t_k . The number of bombardments for each value of d_α was mostly between 5 and 10. The results, expressed as count numbers in the first channel divided by the summed monitor value are shown in Figs. 11 to 14. The background and longer-lived activity present is also plotted as the mean value of the counts in channel 6 to 10 divided by the total monitor value. In most cases the short-lived activity had decayed to the background level from channel 6 and on. Bombardment series were undertaken at cyclotron radii R_t of 60, 66, 71.5, 80, 89 and 97 cm corresponding to nominal proton energies of 70, 85, 100, 125, 150 and 170 MeV. Curves for 66 and 60 cm radius have the same appearance as those in Figs. 11 to 14, although the yield was markedly less for 66 cm and much smaller for 60 cm. The calibration lines taken with a ThC + C' source are also shown in the figures.

Furthermore, internal calibration lines from longer-lived nuclei are present in the background curves. The presence of the Ac^{222} series is indicated by peaks at approximately 6.96, 7.85 and 8.78 MeV decaying with a half-life of about 5 sec.

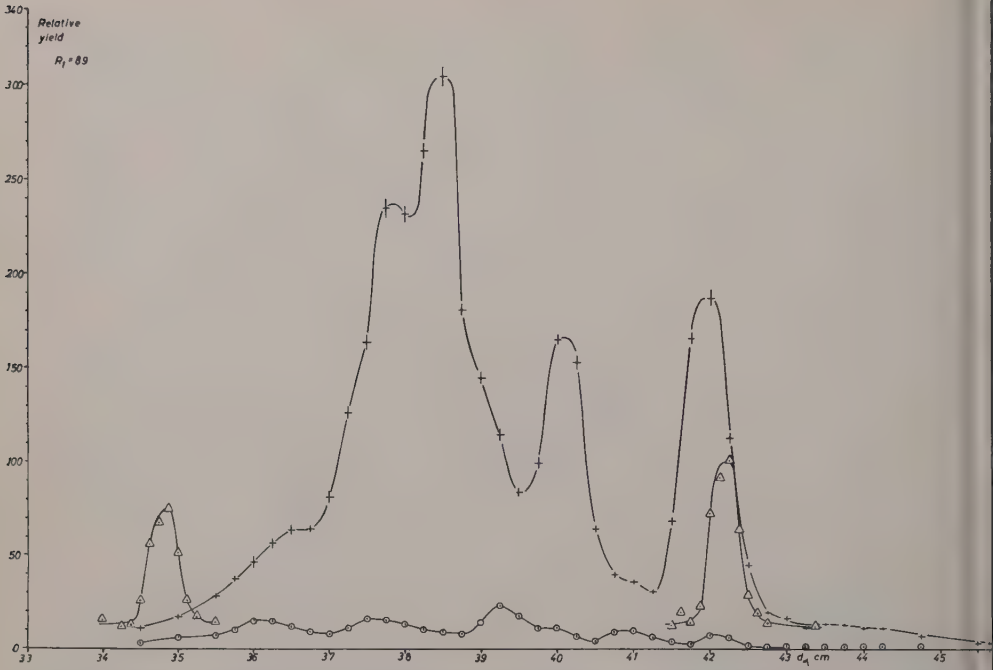


Fig. 12. Th target, relative yield for bombardment radius $R_t = 89$. Same arrangements as in Fig. 11.

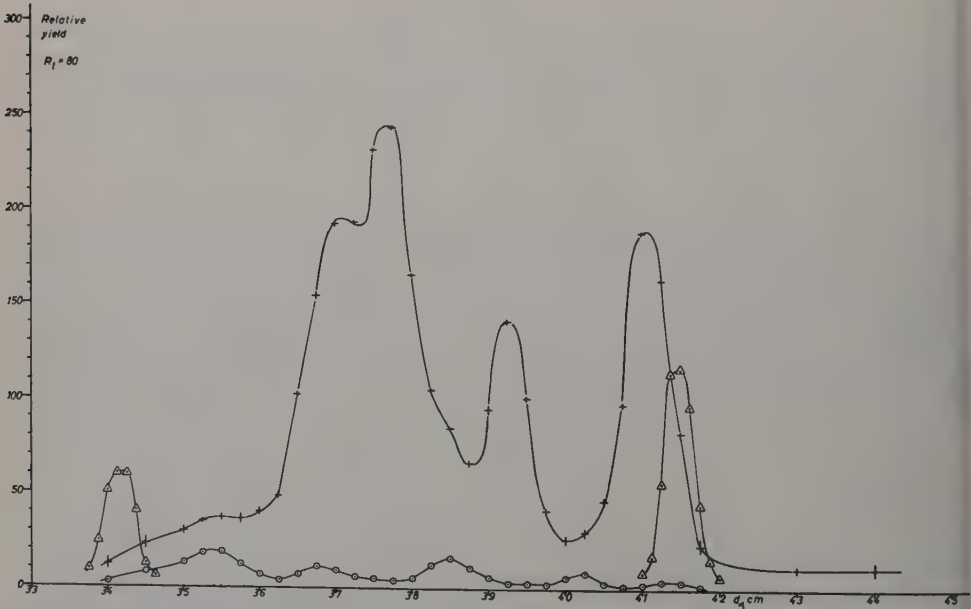


Fig. 13. Th target, relative yield for bombardment radius $R_t = 80$. Same arrangements as in Fig. 11.

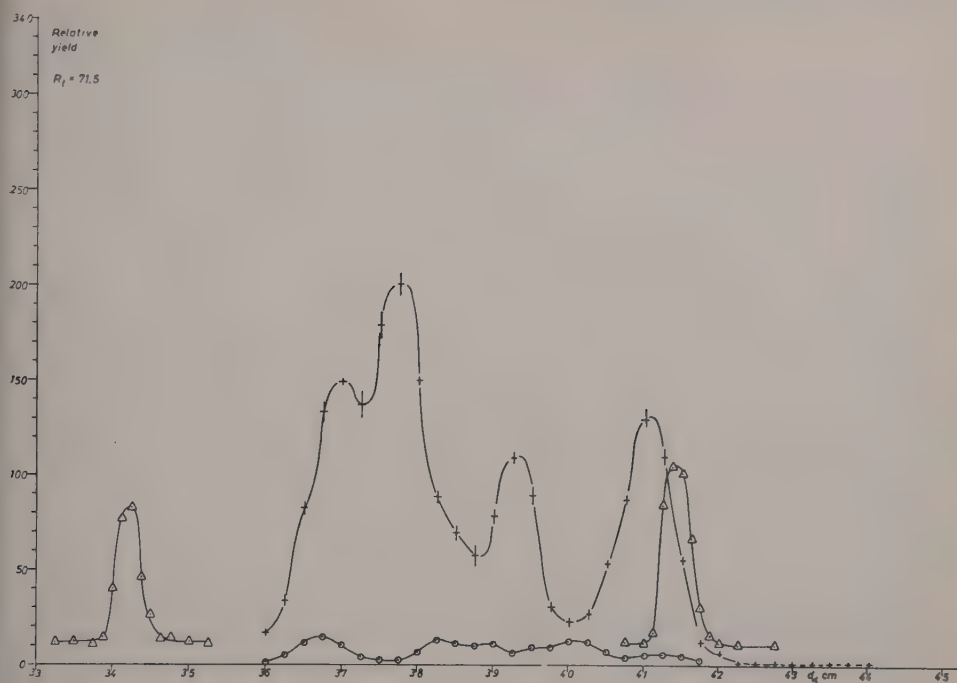


Fig. 14. Th target, relative yield for bombardment radius $R_t = 71.5$. Same arrangements as in Fig. 11.

The Th^{225} 8.0 min. series is indicated by the peak at 8.34 MeV. The other peaks of the series are partly mixed up with other series. The Pa^{227} 38 min. series is pointed out by the edge at approximately 8 MeV and by the shoulder at 7.3 MeV. The presence of the Th^{226} 31 min. series is also indicated around 7.7 and 7.1 MeV. It is possible to obtain direct information about ratios of production cross sections. In comparing peak heights, however, it should be born in mind that the half-lives are comparable to, or longer than the times between bombardments. This together with irregularities in the irradiation cycling may cause shifts in peak heights. The peaks found most suitable for calibration purposes, apart from the $\text{ThC} + \text{C}'$ source, are those from At^{214} at 8.78 MeV, Po^{213} 8.34 MeV and Ac^{222} at 6.96 MeV and Fr^{218} at 7.85 MeV, the latter being pointed out by the large slopes in background appearing here. In Fig. 11 is drawn, through the $\text{ThC} + \text{C}'$ points, a calibration line for a thin source calculated as previously described together with a displaced one that suits the internal calibration points. There is seen to exist a small shift between the At^{214} 8.78 MeV peak and the calibration Po^{212} 8.78 MeV peak. This corresponds to the mean energy loss in the target, as previously discussed.

As can be seen from Figs. 11 to 14 the ratio of short-lived activity to background and longer-lived activity is rather high. The background conditions were slightly different in the various runs. A slight difference in detector sensitivity may also have existed. This would explain the apparent small sensitivity to short-lived γ -activity witnessed in some of the curves, outside the α -peak region. More accurate information

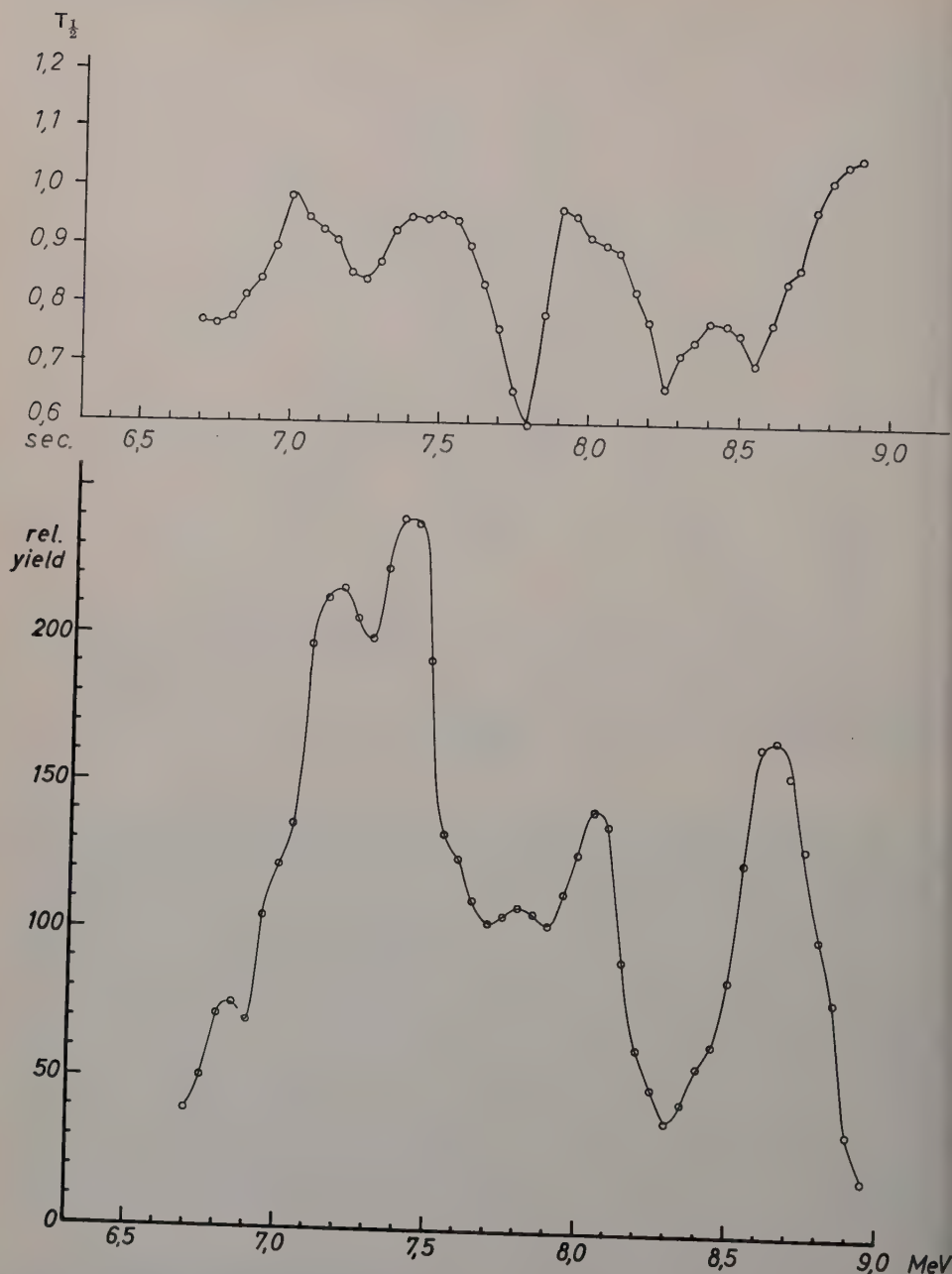


Fig. 15. Th target, bombarded at $R_t = 80$ with $t_s = 6 t_k$ and $t_k = 0.2$ sec. Yield, expressed as decay rate at opening time of first channel divided by the monitor value, as a function of energy. The energy scale was determined from corrected calibration curves, similar to that in Fig. 11. Because of different half-lives for the peaks, the curve should differ from those in Figs. 11-14. The variation of half-life with α -energy is also shown. Max. deviations were ≈ 0.05 sec.

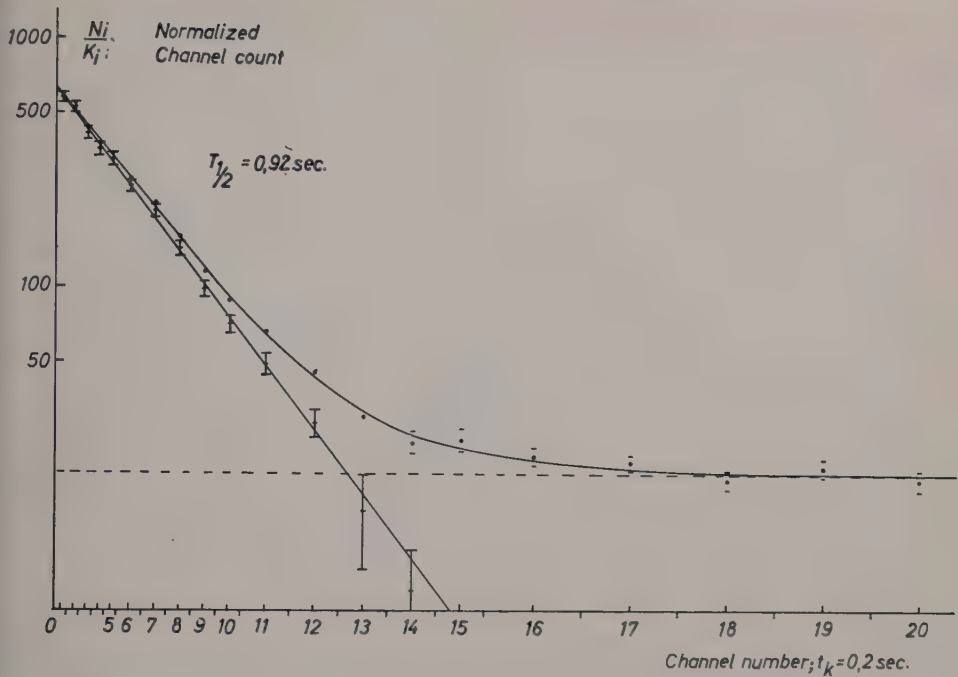


Fig. 16. Typical decay curve obtained in Th bombardments with $t_s = 6 t_k$ and $t_k = 0.2$ sec. The curve is for an α -energy of approx. 7.1 MeV. For good determination of the slope of the background single-bombardment runs were made with subsequent measurements during two or three analyser cycles without bombardments.

about the yield ratios for different irradiation energies was available from other, incomplete curves for different R_t taken during the same experiment day. Concerning the shape of the spectra, no definite difference can be seen between the various curves.

The half-lives varies over the spectra from 0.6 to 1.05 sec., and in some places the decay curves are seen to be composite, with the components in the above range. A further feature is that for the first part of the decay curve the second derivative is slightly negative at the highest peak e.g. around $d_x = 38.5$ for Fig. 11, at approximately 7.4 MeV energy. Typically the count number in the first channel is 20–30 % less than what should be expected from the later channels. The behaviour is what should be expected if a daughter activity is present which has a half-life comparable to that of the parent, as previously discussed (cf. Fig. 10).

In order to determine the half-lives better a second series of experiments at $R_t = 80$ was undertaken in which $t_k = 0.2$ second was chosen, with $t_s = 6t_k = 1.2$ second bombardment time. As in most irradiations the relay pulser described in ref. [1] was used, giving 0.03–0.05 sec. separation between the end of the bombardment and the start of counting. The step in d_x was diminished to ca. 0.125 cm for better peak resolution. The channel-time prolongation system was used. Because of the small differences in the half-lives no attempt was made to resolve composite decay curves. After subtraction of background, a decay line was drawn, with emphasis on the first

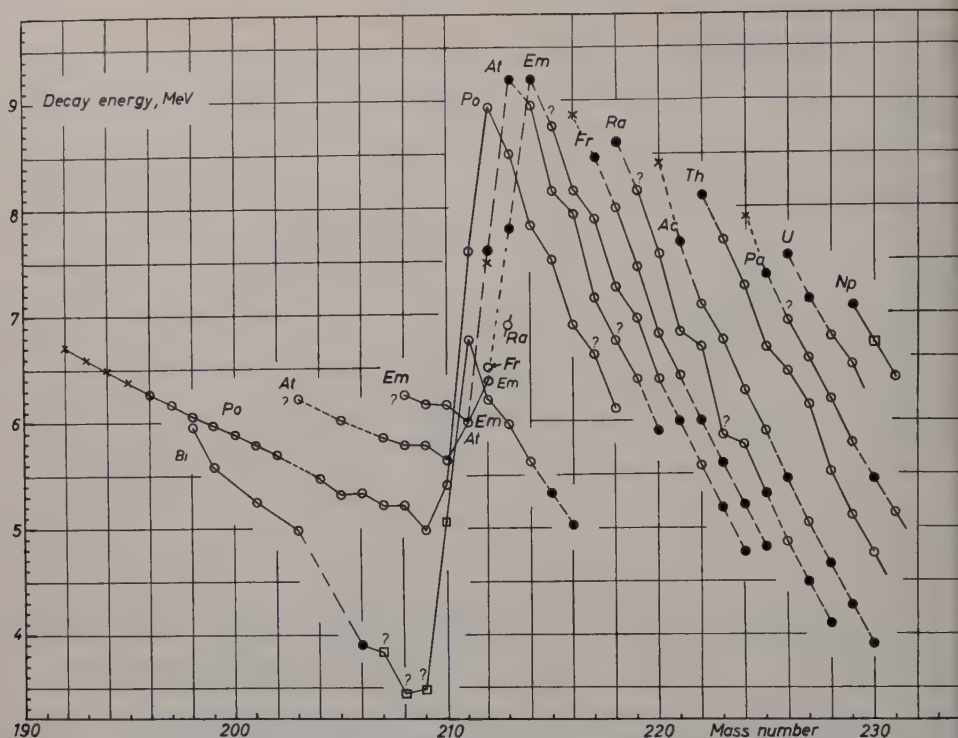


Fig. 17. Alpha decay energy versus mass number. Reproduced with minor alterations from ref. [23]. $\circ$, experimental energy; $\square$, calculated from closed β - α decay cycles or neutron-binding energies; $\bullet$, estimated from systematics; $?$, energy or mass assignment in question; $\times$, discussed in this work.

points, where the statistics are best, even in those relatively few cases where the last points departed definitely from the line, and the half-life thus obtained was noted, together with the y -intercept, i.e. the extrapolated yield at the starting time of counting. The justification for this and for the analysis in fig. 20 is that for two nearly equal half-lives the yields are summed in the composite curve while the half-life obtained is the weighted mean, at least during the first one or two half-lives. If the decays are described by $A_1 e^{-\lambda_1 t}$ and $A_2 e^{-\lambda_2 t}$, respectively, we have

$$A_1 e^{-\lambda_1 t} + A_2 e^{-\lambda_2 t} \approx (A_1 + A_2) e^{-\frac{(\lambda_1 A_1 + \lambda_2 A_2)}{A_1 + A_2} t}$$

as long as

$$\left| \frac{A_1}{A_1 + A_2} (\lambda_1 - \lambda_2) t \right| \ll 1$$

and

$$\left| \frac{A_2}{A_1 + A_2} (\lambda_2 - \lambda_1) t \right| \ll 1.$$

Fig. 15 shows the mean values of yield and half-lives obtained using several incomplete curves covering parts of the spectra. A typical decay curve is shown in

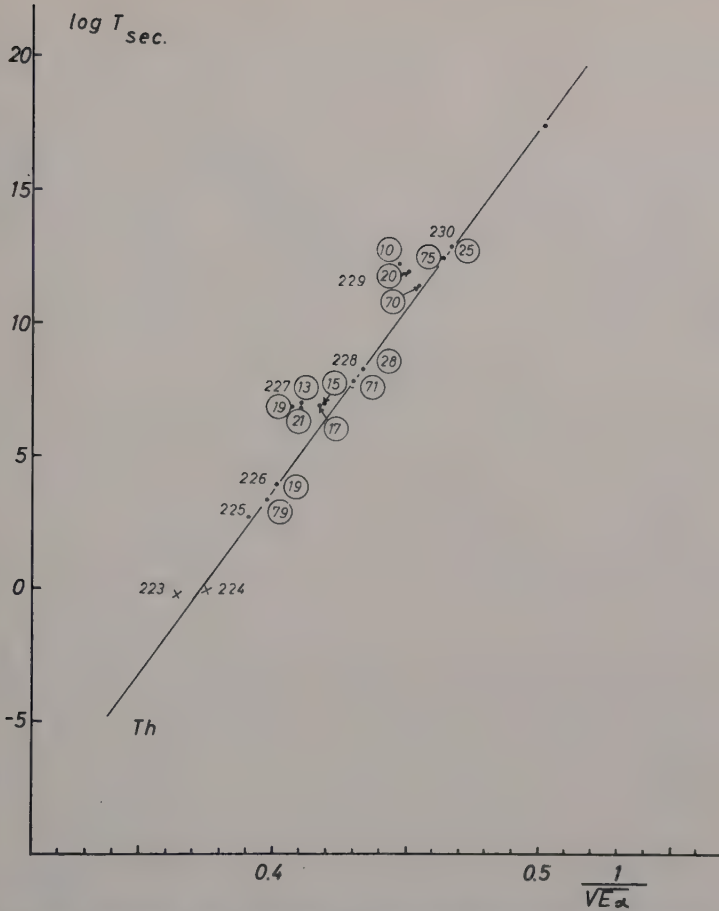


Fig. 18. Plot of the logarithm of the α half-life T_{α} against the inverse root of energy for Th isotopes. Numbers outside circles are mass numbers and those inside the percentage of the total α -decays that is represented by the point in question. $\times$ are points discussed in this work. The straight line is that determined by Fröman [24] for best fit of a family of lines to even-even α -emitters.

Fig. 16. The yield curve was corrected for spectrometer transmission. The trends were well reproduced in the different runs.

The main features of the results in energy, yield and half-life are not in disagreement with the hypothesis that four decay series are involved, those originating from Th^{224} , Th^{223} , Pa^{225} and Pa^{224} , respectively. The reactions needed to reach these nuclei from Th^{232} , i.e. $(p,p8n)$, $(p,p9n)$, $(p,8n)$ and $(p,9n)$, should give rather high yields. The energies of the Th^{224} and Th^{223} series, originating from corresponding uranium nuclei, have been determined by the Berkeley group [20, 21] using chemically separated sources and ionization chamber techniques. The U^{228} - Th^{224} series is best established and is of the even-even type, and hence the ground-state to ground-state transitions are probably most favoured, giving a simple spectra. The energies are given as Th^{224}

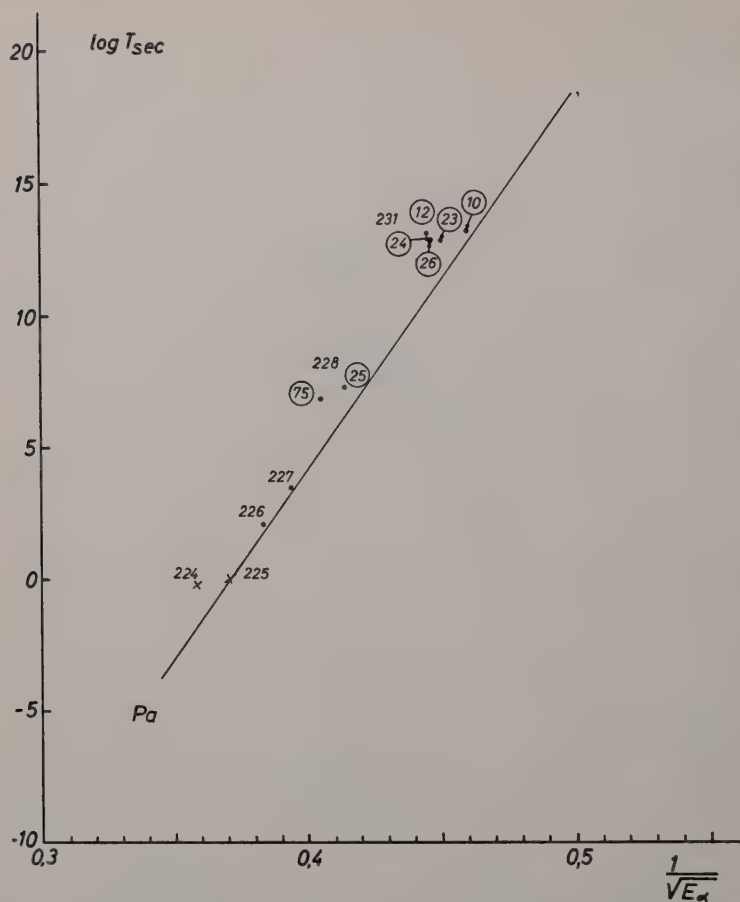


Fig. 19. The same plot as in Fig. 18, but for Pa isotopes.

7.13 ± 0.02 MeV, Ra^{220} 7.43 ± 0.02 MeV, Em^{216} 8.01 ± 0.03 MeV and Po^{212} 8.780 MeV [20, 22]. From α -systematics. Meinke *et al.* [20] estimate the half-life of Th^{224} to about 1 sec. The energies fit well into the common plot [23] of alpha decay energy versus mass number which is reproduced with minor alterations in Fig. 17. Plots of the logarithm of the half-life T against the inverse root of energy for Th and Pa isotopes are illustrated in Figs. 18 and 19, and can be used for rough estimates of half-lives of unknown isotopes. From simplified theory (see ref. [22], p. 36) these plots should be linear and this is rather well satisfied for even-even nuclei [22, 24].

The energies of the even-odd Th^{223} series are given as Th^{223} 7.55 ± 0.1 , Ra^{219} 8.0 ± 0.1 , Em^{215} 8.6 ± 0.1 and Po^{211} 7.434 MeV [21]. Po^{211} is a member of a natural radioactive series and has a half-life of 0.52 sec. This isotope also has a 25 sec. isomeric state decaying with a 7.1 MeV α [25] and from Fig. 2 in ref. [21] there seems to be some evidence that this isomer is also fed to a small amount from Em^{215} . This would probably mean that a corresponding amount of the Em^{215} 8.6 MeV α 's would be

decreased to approximately 7.3 MeV. The decay of Th^{223} should be hindered compared to the even-even Th isotopes and it is seen from Fig. 18 that the hindrance factor, if the half-life is about 1 sec., should be about the same as for other even-odd Th isotopes.

The energies of the Pa^{225} series have been estimated from closed α - β decay cycles by Glass, Thompson and Seaborg [23] to be for Pa^{225} 7.24, Ac^{221} 7.54, Fr^{217} 8.29 and At^{213} 9.02 MeV. Those of the Pa^{224} series can be extrapolated from their curves of energy versus mass number (see Fig. 17) to be approximately 7.75, 8.2, 8.7 and 7.45 MeV for Pa^{224} , Ac^{220} , Fr^{216} and At^{212} respectively. At^{212} has previously been identified with a 0.25 sec. α -activity found in α bombardment of Bi (see [26]). The half-life of Pa^{225} can be estimated from Fig. 19 to be of the order of 1 sec. The Pa^{224} half-life could be of the same order of magnitude in view of the fact that as a general rule the decay of odd-odd nuclei is still more hindered than that of even-odd and odd-even nuclei.

An attempt to explain the experimental results on the basis of the four above-mentioned series is shown in Fig. 20 where lines with the shape of the internal calibration lines are summed to give a resultant yield curve. The peak amplitudes for the Th^{224} , Th^{223} and Pa^{224} series are chosen to give best fit to the experimental curve and the ratios are about what should be expected from the production reactions. For best fit to the experimental curves and to explain the apparent absence of the At^{213} peak, estimated to 9.02 MeV, members of the Pa^{225} series had to be drawn with different peak heights. An explanation for this could be K -capture of Pa^{225} and its daughter or the existence of isomeric states, in which case the two lowest-energy peaks in Fig. 20 might be involved. In order to solve the problem experiments with better resolution would be desirable. Attempts in this direction have failed because of the smaller yield and hence relatively increased sensitivity to background. This was enhanced by appearing short circuits in the cyclotron magnet. These give displacement of the beam, causing fraction of it to strike the cyclotron dee, hence increasing the γ background.

However, considering the above attempted explanation a few things could be said. The presence of the Th^{224} and Th^{223} series seems unambiguous in the two highest-energy peaks. The strongest evidence for Pa^{224} seems to be the presence of a peak with markedly short half-life, 0.6 sec., at the proper place in the spectrum where a member of the other series could hardly be found. Fr^{216} , descendent of Pa^{224} , also fits well into the valley between the Po^{212} and Em^{215} peaks and gives about the right value for the half-life. Low values for the half-life are also found at the other suggested places for the Pa^{224} series. The presence of a grow-in activity at the highest peak is an indication of 0.52 sec. Po^{211} , daughter product of Th^{223} , and possibly also of 0.25 sec. At^{212} , descendent of Pa^{224} . The Ac^{220} peak had to be divided into two for best fit to the experimental curve. This is however not in disagreement with the fact that for even-odd, odd-even and odd-odd nuclei, the ground state transition is often less abundant than transitions to excited states. From the plot of half-life the most probable half-lives for the different series are 1.05 ± 0.05 sec. for Th^{224} , 0.6 ± 0.05 sec. for Pa^{224} , and for Pa^{225} and Th^{223} 0.8 ± 0.1 and 0.9 ± 0.1 sec. respectively. The absence of At^{213} , with an estimated energy of 9.02 MeV [23], is noticeable. This is in contradiction with the results of Keys [27] who found an energy of 9.2 MeV, from the range in emulsions.

The relative production cross sections were determined from the first series of bombardment, using curves from the same experiment. The result is shown in Fig. 21,

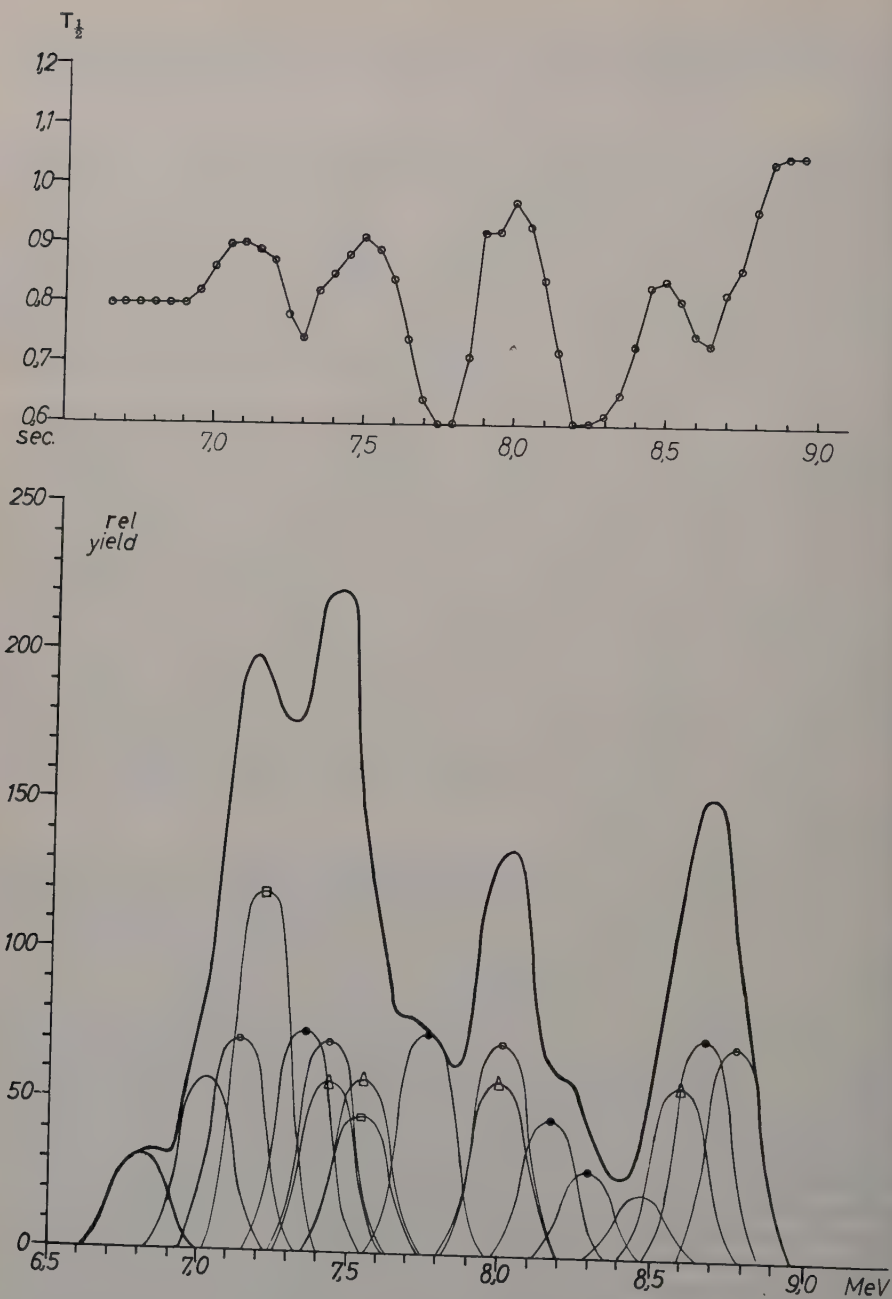
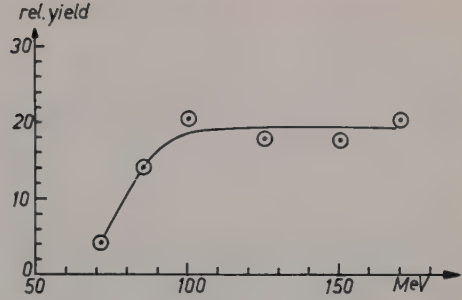


Fig. 20. Theoretical yield curve, assuming certain energies E and peak heights A for members of the series from, respectively, Th^{224} , marked ○, Th^{223} , marked △, Pa^{225} , marked □, and Pa^{224} ,

Fig. 21. Relative cross sections as a function of nominal cyclotron energy for α -activities induced in Th. The lowest-energy point was plotted assuming the same effective beam as for 85 MeV. The spread in the beam energy of the cyclotron causes a beam intensity with a half-width of 10–15 MeV and the peak intensity at ≈ 15 MeV lower energy than the nominal value [28].



and was deduced from the counts of the first channel at the peaks. The flip-target and flip-monitor were used in obtaining a reference value for the current. A correction was made for variation of detection efficiency with radius, using a set of calibration measurements at different radii. The efficiency was found to be nearly constant. It is assumed that the detector efficiency varies little for the small variation in beam pattern expected. The effective beams were determined using a series of aluminium foil bombardments at different radii and measuring the Na^{24} activity in a 4π counter. The beam was calculated from the $\text{Al}^{27}(p,3pn)\text{Na}^{24}$ cross section values given by Hicks *et al.* [15]. Two irradiation series were made, first using foils slightly thicker and then slightly thinner than the value used in the Th bombardments, and the mean value was used. The effective beam had a flat maxima around 125 MeV and the current here was about $5 \mu\text{A}$ in the bombardments. In order to obtain the absolute cross section, the detection efficiency was determined from measurements on a $\text{ThC} + \text{C}'$ calibration source both in the cyclotron and in a scintillation detector with known geometry. The phosphor was a thin plastic and a pulse height analyser was used to count all α -particles. The detection efficiency, including solid angle, was found to be 2×10^{-4} . The cross section was calculated from Eq. (2) to be 100 milli-

marked $\bullet$, and using an internal calibration line as standard line. The assumed energies and peak heights are:

	Th ²²⁴	Ra ²²⁰	Em ²¹⁶	Po ²¹²	Th ²²³	Ra ²¹⁹	Em ²¹⁵	Po ²¹¹
<i>E</i> MeV	7.13	7.43	8.01	8.78	7.55	8.0	8.6	7.43
<i>A</i> _{rel}	70	70	70	70	57	57	57	57

	Pa ²²⁴	Ac ²²⁰	Fr ²¹⁶	At ²¹²	Pa ²²⁵	Ac ²²¹			
<i>E</i> MeV	7.76	8.2	8.26	8.7	7.35	7.21	7.55	8.43	7.03
<i>A</i> _{rel}	73	40	33	73	73	120	45	30	35
								30	30

The theoretical weighted mean values for the half-life are also shown. The values for the half-lives assumed in the calculations are for Th²²⁴ and descendants 1.05 sec.; Th²²³ and descendants 0.9 sec.; Pa²²⁴ and descendants 0.6 sec.; Pa²²⁵ and Ac²²¹ 0.8 sec. which is also the value chosen for the peaks at 8.43, 7.03 and 6.81 MeV. The essential features of the curves are seen to be the same as in fig. 15.

barns, for the composite highest-energy peak. The error is estimated to be less than a factor of 2.

The rising of the exitation curve in Fig. 21 appears at about the estimated energy for the involved reactions, using the binding energies of ref. [23] and allowing for some kinetic energy to the evaporated particles.

Radium

An approximately 0.5 mg/cm² thick layer of RaBr₂ on 0.008 mm thick aluminium was prepared by evaporating a solution to dryness. The target thus obtained was slightly uneven in thickness, causing the resolution to be somewhat worse.

At a bombardment energy of 125 MeV a number of previously known α -emitters were obtained. At 8.8 MeV was obtained a peak evidently due to At²¹⁴, descendent of Ac²²², produced in the bombardment with a (*p*,5*n*) reaction from Ra²²⁶. The half-life here, and at the places for Ac²²² and Fr²¹⁸, was somewhat shorter than the previously reported 5.5 ± 0.5 sec. [21], the value obtained here being 4.2 ± 0.5 sec. This is in agreement with that obtained from the Th bombardments. A peak at approximately 8.34 MeV with a half-life of 28 ± 2 sec. was assigned to Po²¹³, descendant of Ra²²¹. At 7.85 MeV Fr²¹⁸, daughter of Ac²²², was found. Around 7.75 MeV was obtained 7.74 MeV Em²¹⁷ and 7.79 MeV At²¹⁶, daughters of Ra²²¹ and Fr²²⁰ respectively. At 7.43 MeV a 0.56 ± 0.04 sec. peak was obtained which was assigned to Po²¹¹, product of Ra²¹⁹, whose half-life is estimated to be short enough, ≈ 1 ms, to explain its absence in the spectra. Around 7.12 MeV the 39 ± 4 sec. activity from Em²¹⁸, daughter of Ra²²², appeared. Ac²²² was obtained at the expected place, about 6.96 MeV. A broad peak at 6.5–6.7 MeV with half-life varying between 28 and 39 sec. is explained by 6.71 MeV Ra²²¹, 6.51 MeV Ra²²² and 6.69 MeV Fr²²⁰. An unassigned activity decaying with a half-life of 7 ± 2 sec. is found at 6.35 MeV.

Table 1. Results of Radium bombardments.

Alpha energy MeV ± 0.04 MeV	8.78	8.34	7.85	7.74–7.79	7.43
Half-life sec.	4.2 ± 0.5	28 ± 2	4.2 ± 0.5	≈ 28	0.56 ± 0.04
Assignment	At ²¹⁴	Po ²¹³	Fr ²¹⁸	Em ²¹⁷ –At ²¹⁶	Po ²¹¹
Production reaction	Ra ²²⁶ (<i>p</i> ,5 <i>n</i>)Ac ²²²	Ra ²²⁶ (<i>p</i> , <i>p</i> 5 <i>n</i>)Ra ²²¹	Ra ²²⁶ (<i>p</i> ,5 <i>n</i>)Ac ²²²	Ra ²²⁶ (<i>p</i> , <i>p</i> 5 <i>n</i>)Ra ²²¹ Ra ²²⁶ (<i>p</i> ,2 <i>p</i> 5 <i>n</i>)Fr ²²⁰	Ra ²²⁶ (<i>f</i> , <i>p</i> 7 <i>n</i>)Ra ²²¹

(Table 1, contin.)

Alpha energy MeV ± 0.04 MeV	7.12	6.96	6.7–6.5	6.35
Half-life sec.	39 ± 4	4.2 ± 0.5	28–39	7 ± 2
Assignment	Em ²¹⁸	Ac ²²²	Ra ²²¹ (6.71 MeV); Ra ²²² (6.51 MeV) Fr ²²⁰ (6.69 MeV)	
Production reaction	Ra ²²⁶ (<i>p</i> , <i>p</i> 4 <i>n</i>)Ra ²²²	Ra ²²⁶ (<i>p</i> ,5 <i>n</i>)Ac ²²²	Ra ²²⁶ (<i>p</i> , <i>p</i> 5 <i>n</i>)Ra ²²¹ ; Ra ²²⁶ (<i>p</i> , <i>p</i> 4 <i>n</i>)Ra ²²² Ra ²²⁶ (<i>p</i> ,2 <i>p</i> 5 <i>n</i>)Fr ²²⁰	

Uranium

The target was prepared in the same way as the Th target and with the same dimensions, 0.5 mg/cm² on 0.0005" aluminium. The bombardments were undertaken in an aim to find ancestors to the activities obtained from thorium. No activities with half-lives in the region of a second were found although this could be expected from lifetime systematics, at least for the even-even nuclei U²²⁶. The competition of fission becomes increasingly important as the atomic number increases. For every particle that is to be evaporated from the excited nuclei there is competition between evaporation and fission processes. From a collection of data for less neutrondeficient products obtained in irradiations of targets of different atomic number the probabilities are found to be in the mean about equal for uranium [29]. This means a large decrease of the yield if many neutrons are to be evaporated. For thorium the evaporation process is found to be in the mean about 10 times as probable as the fission process [29]. For the range of half-lives found, above 1 min., ordinary procedures, involving chemical separations and measurements in a ionization chamber or spectrometer would be possible. The results here are several complex decays with half-lives in the range 1–3 min. and also longer, about 15 min. These are difficult to resolve because of the small yield and ratio of decaying activity to background.

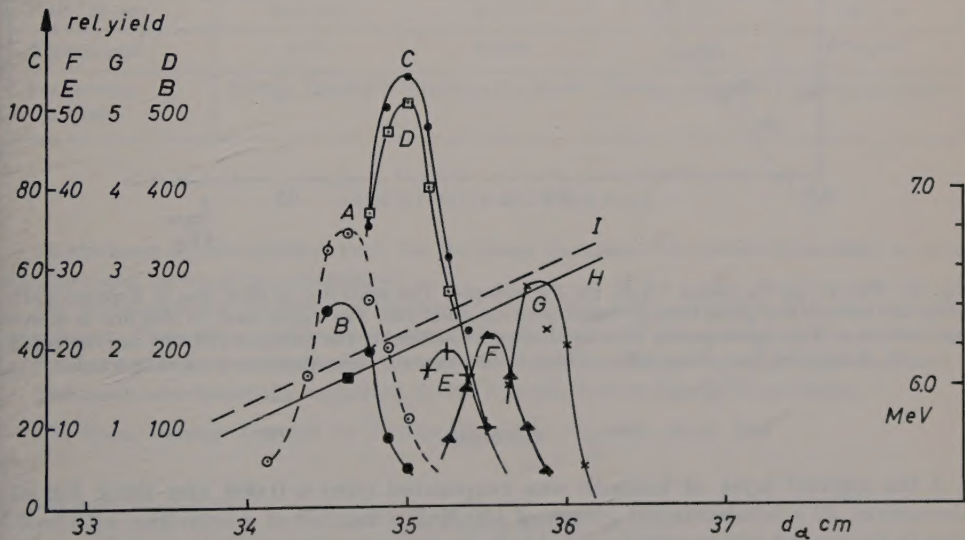


Fig. 22. Analysis of composite decay curves obtained in Bi bombardments. The yield, expressed as the extrapolated decay rate at the start of counting, is plotted for each half-life as a function of α -energy. A is a Th C + C' calibration peak and H and I are uncorrected resp. corrected calibration lines. Peak B is assigned to Po¹⁹⁶. C and D are obtained with different irradiation times and have the half-life assigned to Po¹⁹⁵. E, F and G are assigned to Po¹⁹⁴, Po¹⁹³ and Po¹⁹². The bombardment times used in obtaining the different peaks are unequal unless the scale is the same, and correction for this is made in calculation of cross section ratios.

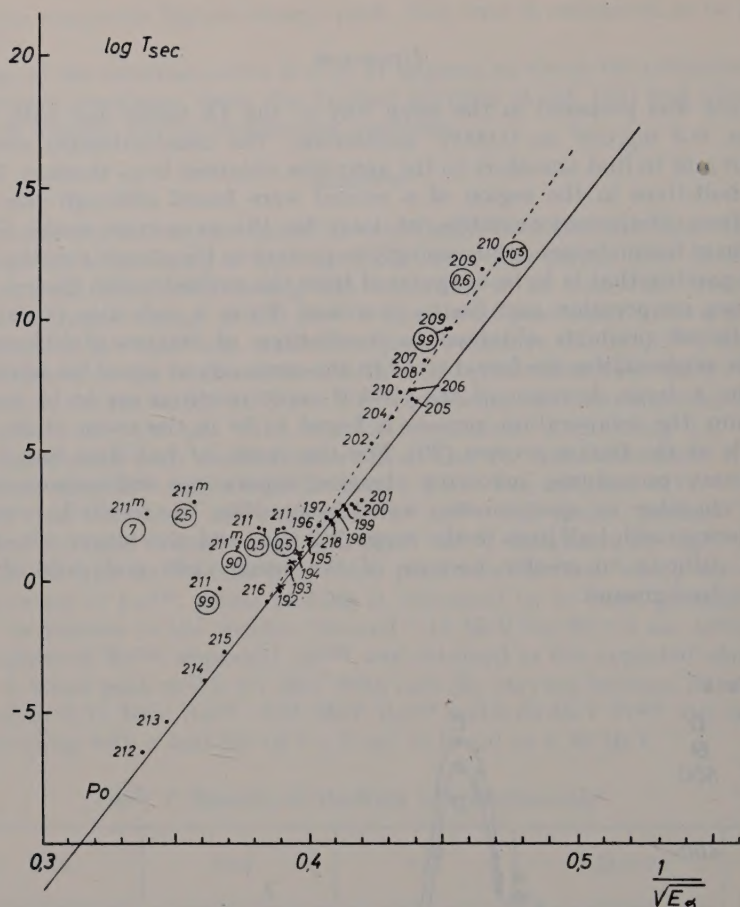


Fig. 23. Plot of $\log T_{\alpha}$ versus $1/\sqrt{E_{\alpha}}$ for Po isotopes. The solid line is that due to Fröman [24], while the broken line gives best fit below neutron shell 126. The upper part of this line is above the solid line. This corresponds to a small nuclear radius. If the isotopes 198–201 are corrected for K -capture branching ratio, which is not known, the points are moved upward.

Bismuth

A 0.5 mg/cm² layer of bismuth was evaporated onto a 0.008 mm thick foil of aluminium. At a bombardment energy of 150 MeV a number of α -activities with half-lives in the second region were found. At the lowest α energies investigated, composite decay curves were found, consistent with the previously reported 1.9 min. 6.14 MeV α -ray, attributed to Po¹⁹⁶ [30], and 4 min. 6.04 MeV attributed to Po¹⁹⁷ [31]. At higher energies composite activities of decreasingly shorter half-lives were found. It was possible to resolve these into peaks having half-lives and energies of 30 ± 4 sec., 6.26 MeV; 13 ± 2 sec., 6.38 MeV; 4 ± 1 sec., 6.47 MeV; and 0.5 ± 0.1 sec., 6.58 MeV (Fig. 22). The energy calibration line was constructed from the curve for a calibration

source and using the same mean energy loss as found in the thorium bombardments. The position of the Po^{196} peak was found to be in accordance with the line thus obtained. The cross sections were found to be in the approximate ratio of 1:0.4:0.2:0.08 starting from the 30 sec. peak, for this bombardment energy. The absolute cross section for the 30 sec. peak was found to be of the order of 25 millibarns. In view of the difficulty in analysing complex decay curves, with the small distance between peaks compared to the resolution, the results should be considered as preliminary. The energy accuracy is estimated to ± 40 keV.

It seems most probable that the activities are due to Po isotopes. In subsequent bombardments using Pb, Tl, Au and Pt as targets no measurable α decay was found with this method. It is found that the measured energies fit rather well into plots of decay energy versus mass number for Po isotopes (Fig. 17) if it is assumed that the measured isotopes are Po^{195} , Po^{194} , Po^{193} and Po^{192} for the 30 sec., 13 sec., 4 sec. and 0.5 sec. activities, respectively. The decay times are in line with what should be expected from plots of $\log T$ versus $1/\sqrt{E_\alpha}$ for Po isotopes (Fig. 23) below the closed neutron shell $N = 126$. The isotopes just below the shell lie above the line for the isotopes above the shell. This corresponds theoretically to smaller nuclear radii.

Table 2. Results of Bismuth bombardments.

Alpha energy MeV ± 0.04 MeV	6.58	6.47	6.38	6.26
Half-life sec.	0.5 ± 0.1	4 ± 1	13 ± 2	30 ± 4
Assignment	Po^{192}	Po^{193}	Po^{194}	Po^{195}
Production reaction	$\text{Bi}^{209}(p, 18n)\text{Po}^{192}$	$\text{Bi}^{209}(p, 17n)\text{Po}^{193}$	$\text{Bi}^{209}(p, 16n)\text{Po}^{194}$	$\text{Bi}^{209}(p, 15n)\text{Po}^{195}$

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